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# Electronic transport at low temperature below the field-driven superconductor–insulator transition in thin a-$Mo_xSi_{1-x}$ films

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**Abstract**

We have shown so far that thin amorphous (a-)$Mo_xSi_{1-x}$ films exhibit the field-driven superconductor–insulator transition (SIT) at zero temperature ($T = 0$), while the existence of a *metallic* quantum–vortex–liquid at $T = 0$ has been reported in several thin amorphous films. Here we reexamine the possibility of the metallic phase by measuring the $T$ dependence of resistance $R(T)$ for the thin a-$Mo_xSi_{1-x}$ films with various transition temperatures $T_{c0}$ in fields $B$ below the critical field of the "SIT". We find that the value of $T_{c0}$ dominates $R(T)$ at low $T$. For films with $T_{c0}$ larger than 1.0 K, the activation energy $U$ derived from the slope of the Arrhenius plot of $R$ is constant over the whole $T$ region, while for films with $T_{c0} < 1.0$ K, $U$ exhibits a discontinuous decrease below about 0.1 K; however, $U$ remains constant and positive down to the lowest $T$. All of the data are consistent with the picture of the field-driven SIT.


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*Keywords:* Superconductor–insulator transition; Pinning; Two dimensions; Amorphous films

## 1. Introduction

In two-dimensional (2D) superconductors the existence of a metallic quantum–vortex–liquid (QVL) phase at zero temperature ($T = 0$) has attracted considerable attention. This is based on the recent experimental studies for several amorphous thin (2D) films which report the $T$-independent or weakly $T$-dependent resistance ($R$) suggestive of $T = 0$ metallic phase in fields ($B$) below the (putative) field-driven superconductor–insulator transition (SIT) $B_c$ [1–6]. This problem is important because it challenges the traditional

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picture of the field-driven SIT [7,8]. Several theories predict that the metallic phase in 2D is a Bose-metal phase in which Cooper pairs lack phase coherence [9,10], while there is a theory which precludes the possibility of an intermediate metallic vortex phase at $T = 0$ [11]. Now, it seems that the existence of the metallic QVL phase in 2D has been widely accepted in the field.

On the other hand, we have reported the experimental data in favor of the field-driven SIT (i.e., absence of a metallic phase) at $T = 0$ in ultrathin films of amorphous (a-)$Mo_xSi_{1-x}$ [12]. To date, we have measured many thin films, but we have not observed the apparent $T$-independent $R$ at low $T$ or upward curvature in the Arrhenius plot of $R(T)$ which persists down to $T \to 0$. We thus consider that, independent of the theory, it is important to clarify experimentally what makes the difference between the low-$T$ transport properties in the similar thin films studied by us and by other groups. In more detail, in our thin films all of the $R(T)$ data in fields below $B_c$ show the behavior to approach zero as $T \to 0$. We note, however, that for some particular films the slope of the Arrhenius plot of $R(T)$, that is the activation energy $U$, exhibits a discontinuous decrease at low $T$, typically around 0.1 K [12,13]. Since this behavior might be the indication of the metallic phase in our thin a-$Mo_xSi_{1-x}$ films, it is important to study the experimental condition causing such a decrease in $U$.

In this work, we have measured the resistance $R$ for thin amorphous $Mo_xSi_{1-x}$ films with different $T_{c0}$ and $R_n$, at low temperature $T$ in fields $B$ below $B_c$, where $T_{c0}$ and $R_n$ are the mean-field transition temperature and normal-state resistance at 10 K, respectively. The activation energy $U$ derived from the slope of the Arrhenius plot of $R$ (at $T > 0.1$ K) obeys the 2D functional form $U = U_0 \log(B_c/B)$. The value of $U_0$ is uniquely determined by $T_{c0}$ and thus the value of $T_{c0}$ dominates $R(T)$ at low $T$. We find a threshold value of $U_0$ (or $T_{c0}$), below which $U$ exhibits a discontinuous decrease at $T < 0.1$ K. We note, however, that $U$ in $B$ ($<B_c$) remains constant and positive down to the lowest $T$, implying that $R(T)$ approaches zero as $T \to 0$. This result is consistent with the picture of the field-driven SIT, in which the $T = 0$ metallic phase exists only at $B_c$.

## 2. Experimental

The samples used in this study were two types of 4-nm-thick $Mo_xSi_{1-x}$ films: (i) films 1–4 and (ii) FILMs 1 and 2. All these films were prepared by coevaporation of pure Mo (99.95%) and Si (99.999%) onto a glass substrate. In particular, for FILMs 1 and 2 the substrate was rotated at 200–300 rpm during deposition with an evaporation rate 1 nm/min in order to improve the homogeneity of the ultrathin film [14]. The structure of the thin films was confirmed to be amorphous by transmission electron microscopy and electron diffraction. Measurements were made by four-terminal ac lock-in techniques at 19 Hz with an applied current of 10 nA, which was well within the ohmic regime. The normal-state sheet resistance $R_n$ at 10 K, the mean-field transition temperature $T_{c0}$, and the critical field $B_c$ of the SIT range from 779 to 1313 Ω, 0.14 to 1.86 K, and 1.0 to 5.1 T, respectively. Here $T_{c0}$ is determined from the linear fit of the data to $\Delta G \sim T_{c0}/(T - T_{c0})$, where $\Delta G = R^{-1} - R_n^{-1}$ [15].

## 3. Results and discussion

Fig. 1(a) and (b) shows the Arrhenius plot of the resistance $R(T)$ for film 1 with $R_n = 779$ Ω, $T_{c0} = 1.86$ K, and $B_c = 5.1$ T and for FILM 1 with $R_n = 830$ Ω, $T_{c0} = 0.97$ K, and $B_c = 3.6$ T, respectively, in various perpendicular fields. The $R(T)$ of film 1 in fields between 4 and 5.1 T ($=B_c$) follows the activated exponential form $R(T) \propto \exp(-U/T)$ down to the lowest $T$ measured, as shown with the straight lines in Fig. 1(a). The activation energy $U$ obeys the 2D functional form $U = U_0 \log(B_c/B)$ in fields below $B_c$. For FILM 1, however, $U$ in fields $B$ between 1.5 and 3.6 T ($=B_c$) exhibits a discontinuous decrease below about 0.1 K, as seen in Fig. 1(b). The strength of quantum fluctuations for both films is expected to be similar to each other because of the same thicknesses and close values of $R_n$ [16]. Thus, in